Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 57 (2014) 850 – 859
Energy Procedia

2013 ISES Solar World Congress

Optimizing the energy portfolio of the Mexican electricity sector by 2050 considering CO_2eq emissions and Life Cycle Assessment

Edgar Roberto Sandoval García[a*], Arturo Morales-Acevedo[a,b]

[a]*PhD Program on Science, Technology & Society*
[b]*Electrical Engineering Departmnet*
CINVESTAV- IPN, Av. Inst. Pol. Nacional No. 2508, 07360, Mexico, D. F. , Mexico

Abstract

Today, Mexico is one of the leading countries of the Latin American region in receiving foreign direct investment, with expected GDP growth for the coming years between 4% and 6% per annum, according to estimates published by the OECD and other international organizations. Sustaining such growth demands the strengthening of one of the main pillars of economic development, the National Electricity Sector. To accomplish this growth in the electricity sector will require an energy portfolio that allows for three basic conditions in the sector's planning: reliability, economy and sustainability. To ensure the sustainability of the National Electric Sector, the optimal energy portfolio must meet the CO_2eq emission reduction that the country has adopted based on international commitments. Sources of electricity generation with low water consumption as well as reduced pollutant discharge are needed, given the great importance of water efficiency in energy production. This paper determines an optimal energy portfolio involving conventional technologies, clean technologies and alternative and intermittent renewable technologies, based on a simple optimization model and using variables such as future electricity demand, CO_2eq emissions by source, and taking into account data from several studies of life cycle assessment of the electricity sector, such as energy payback rate and water pollution. The research presented assumes two scenarios of growth in electricity demand of about 350 and 1,150 TW-hours in 2050.

Keywords: energy portfolio; optimization; mexican electricity sector; life cycle assessment; GHG emissions.

* Corresponding author. Tel.: +52-55-5747-3800, ext: 6773
E-mail address: esandoval@cinvestav.mx.

doi:10.1016/j.egypro.2014.10.294

1. Introduction

Mexico is forecasted to become the eight largest economy of the world by 2050 based on an estimated GDP growth higher than 4% per year. Such growth has been projected on traditional economic factors such as, strategic geographic location, trade agreements, natural resources, competitive labor costs and young population [1], [2]. In recent decades increased trade and foreign direct investment resulting from globalization have failed to reduce the degree of inequality and poverty among population, conditions that have actually grown (people in poverty increased from 48.8 to 52 million between 2008 and 2010) [3].

Currently Mexico faces a double challenge, achieving steady economic growth in a sustainable way (Green Growth), using natural resources efficiently to ensure human well-being, and at the same time decreasing environmental risks and ecological scarcities [4].

Delineating a Green Growth path could be complex and multipart, but priorities must be defined. A starting point is to quantify externalities and value natural assets for the long-run services they provide, increasing human capital, and quickly adopting and developing more environmentally sustainable technologies, goods, and services [5].

One of the pillars of Mexico´s Green Growth path will be the energy sector, where an especially important element will be power generation and the technologies on which it is based, taking into account the global goals of energy policy: energy security, economic viability and social and environmental acceptability.

Like any other anthropogenic activity, electricity generation can cause environmental problems or external effects. One way to analyze the negative effects on the environment by anthropogenic activities is through Life Cycle Assessment (LCA). The objective of LCA is to describe and evaluate the overall environmental impacts of a certain action by analyzing all stages of the entire process from raw material supply, production and transport, and energy generation to recycling and disposal stages [6].

The results of LCA, together with other factors such as cost and performance data should be considered by decision-makers in the search for the most economical solution from a societal perspective [7]. In the light of the considerations discussed above, we propose a framework in which Mexico´s electricity sector and in particular its generation portfolio can be evaluated taking into consideration Green Growth and LCA factors. In this paper we propose to optimize the generation portfolio considering for each technology: water consumption and pollution (key pollutants), air pollution (CO_2 eq. data), energy payback rate and electric generation potential (MWh).

2. Methodology

Given the international commitments to GHG emissions reductions that the country has by law, in addition to the global trend to grow in a sustainable way, Mexico needs several methods for measuring and assessing the current and future effects of energy use on human and the environment. That is why future selection of power fuels and associated technologies for the production, delivery and use of energy services, requires studies taking into account economic, social and environmental consequences, and the risk coupled in the process [8]. This study aims to contribute to the definition of sustainability indicators in the generation of electricity through a methodology that was simple, but which in turn optimizes based on various restrictions, so that it could quickly obtain a good estimate of the optimum energy portfolio, that satisfies the required GHG emission levels to 2050 and also minimize the use of water and its pollution using the most appropriate technologies.

Thereby the equations defining the modeling process were:

- GHG emissions, objective value by law to 2050

$$a_gx_1+b_gx_2+c_gx_3+d_gx_4+e_gx_5+f_gx_6+g_gx_7+h_gx_8+i_gx_9+j_gx_{10} = k_g \quad (1)$$

- Water consumption (minimum value)

$$a_wx_1+b_wx_2+c_wx_3+d_wx_4+e_wx_5+f_wx_6+g_wx_7+h_wx_8+i_wx_9+j_wx_{10} <= k_w \quad (2)$$

- Water pollution (minimum value)

$$a_px_1+b_px_2+c_px_3+d_px_4+e_px_5+f_px_6+g_px_7+h_px_8+i_px_9+j_px_{10} <= k_p \quad (3)$$

- Energy Payback Rate (EPR, maximum value). [Maximum EPR was calculated by minimizing the portfolio´s set up energy. EPR is the ratio of total electric power produced during the life cycle of the technology compared to generating electricity that is required to construct the plant, operate, maintain, supply it with fuel and decommission it ($MWh_{life\ cycle}$ / $MWh_{set\ up}$)].

$$a_ex_1+b_ex_2+c_ex_3+d_ex_4+e_ex_5+f_ex_6+g_ex_7+h_ex_8+i_ex_9+j_ex_{10} <= k_e \quad (4)$$

Also, since the number of products built must be nonnegative:

$$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10} >= 0$$

Where participation by type of technology in the energy portfolio was given by:

Technology	GCC	Coal	Nuclear	Wind	SPV	ST	Biomass	Small-Hydro	GST	HD
(MWh)	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}

*GCC: Gas Combined-cycle, SPV: Solar Photovoltaic, ST: Solar Thermal, Residual biomass, GST: Geothermal Steam Turbine, HD: Hydroelectric Dam.

And,

$a_g, b_g, \ldots j_g$: Carbon equivalent emissions factor per type of technology (ton CO_{2eq}/MWh)

$a_w, b_w, \ldots j_w$: Water consumption factor per type of technology (L_{water}/MWh)

$a_p, b_p, \ldots j_p$: Water pollution factor per type of technology (ton $_{pollutants}$/MWh)

$a_e, b_e, \ldots j_e$: EPR factor per type of technology ($MWh_{set\ up}$ / $MWh_{life\ cycle}$).

Because of the linearity of the system of equations posed above, the optimal portfolio modeling for power generation by 2050 was performed using the Simplex algorithm developed by George Dantzig in 1947. The method is particularly applicable to problems involving interacting variables. Determine the response to be optimized and subsequent identification of variables affecting it and the limits of each variable, are the main steps involved in the method [9]. Moreover, the simplex algorithm features a robust method that does not rely on derivatives to provide function minimization for any dimensional space order [10]. This study took advantage of the practicality of the Simplex algorithm to solve a number of multivariable linear equations. The optimization was performed to minimize one objective function value at a time subject to various restrictions. The principal constraints included in the model were:

- Maximum potential electric generation by technology type. For example, the Law for the Use of Renewable Energy and Energy Transition Financing (LAERFTE) [11] imposes a maximum of 50% on the share of fossil fuels in electricity generation by 2050.
- Reducing carbon emissions. Specifically the General Law on Climate Change [12] requires a reduction in greenhouse gases (GHG) emissions of 30% by 2020 and 50% by 2050 in relation to 2000 values.
- Electric power generation requirements to meet the demand. Two growth scenarios from a previous work by Morales-Acevedo [13] were assessed through 2050: 349.8 and 1,147.3 TWh. The first value (349.8 TWh) gives the evolution of energy demand taking into account the increased electrical energy productivity observed in Mexico during the last 15 years (2.9% annually). This increase in electrical energy productivity is due to the technological change in the use of the electrical energy by industry,

buildings and even houses, causing energy saving due to an increased efficiency for energy use. The second value (1,147.3TWh) is determined from the increase rate (4.6% annually) expected by the electricity utility, Comision Federal de Electricidad (CFE), for which they have taken into account the population and economic growth of the country but have not evaluated the technological development. This can be considered a “business as usual” scenario.

Based on the above, the energy portfolio optimization was evaluated in two stages. First calculate the key variables under the main restriction of carbon equivalent emissions: minimum total water consumption (L), minimum water pollution (tons) and maximum energy payback rate (EPR). In a second stage, imposing as secondary constraints the new variables calculated in stage 1, the optimal energy portfolio was determined. The data sources and the approach to estimating the optimal portfolio are further discussed in the following sections.

2.1. Goal and scope of the study

The goal of this study was to determine the optimal energy portfolio that could cover the estimated electricity requirement by 2050 and satisfies limits on CO_2eq emissions, water use and its pollution, and Energy Payback Rate. The LCA impact by technology in the optimal energy portfolio for each MWh generated also was calculated, considering the fuel, construction, operation and decommissioning of the power plant. This was not a revision work of problems and similar methodologies, but a work that aims to contribute to an appropriate process of optimization.

2.2. Maximum potential electric generation by technology type

In 2011, the generation mix was composed as shown in following table 1 [14].

Table 1 Official portfolio in 2011, (259.15 TWh).

Portfolio	GCC	Thermal*	Coal	Nuclear	Wind	Geothermal Steam Turbine (GST)	Hydroelectric Dam (HD)
2011	46.3%	25%	8.5%	3.9%	0.04%	2.5%	13.8%

**Thermal = Gas-turbine, fuel oil & diesel combustion engine, dual.

Maximum potential values for generating conventional technologies by 2050 are defined based on international and local tendencies [15], [16], [17], being as shown in the following table.

Table 2 Conventional technologies, maximum participation by 2050 (% per generation).

Energy technology	Gas combined-cycle	Thermal	Coal	Nuclear
2050	50.0%	0%	9%	10.0%

In the case of Major Hydropower, the model assumes that due to the effects of climate change, dry conditions will prevail in the country, limiting the technology to a production of no more than 35.7 TWh, which was the official generation from 2011 [18]. Maximum potential to be developed by type of Renewable Energy Source (RES) is showed in the following table 3.

Table 3 RES, Generation potential and total capacity.

RES	Generation (GWh)	Total capacity (MW)	Capacity factor (%)
Small Hydro [19]	3,526.1		
Geothermal [20],[21]	48,399 - 183,916.2	6,500 - 24,700	85

Wind turbine [22]	87,600 - 124,392	50,000 - 71,000	20
Solar PV (a)	106,587.8	55,307.1	22
Solar thermal (b)	187,800.0	61,252.4	35
Residual biomass [25], [26]	315,555 - 772,500	42,379 - 103,747	85

(a) Calculations considering 1% of the area of the eight most urbanized cities in the country [23]. Polycrystalline silicon technology was considered.

(b) Assumed 10% of the calculated maximum value of DNI (Direct Normal Irradiation) for Mexico in the publication: Global Potential of Concentrating Solar Power [24]

(c) In the modeling exercise, for Geothermal, Wind and Biomass (residual from agriculture and forestry & direct combustion), the minimum range value was used.

2.3. Reducing GHG emissions

In the present study, CO_2eq emissions by type of generating technology were used. Moreover the CO_2eq emissions from electricity generation had in the period of 1990 to 2010 a CAGR of 2.8% which represented a 72.8% growth compared to 1990, from 66.86 to 115.54 million t CO_2eq/year [27].

According to the data mentioned above, the electric sector generated in 2000 approximately 87.9 million t CO_2eq/year. Consequently, and according the law, by 2050 the Electric Sector´s goal is to reduce its emissions to an approximate value of 43.9 million t CO_2eq/yr. CO_2eq emissions by technology and the portfolio calculated at each stage of optimization were based on published data for the electricity sector in Mexico [28] and the UK´s Parliamentary Office of Science and Technology (POST) [29], which conducted a study of the emissions by type of technology to generate 1 MWh of electricity. The data thus obtained is shown in table 4.

Table 4 CO_2eq emissions from different electricity-generating options (ton/MWh).

Technology	GCC	Coal	Nuclear	Wind	SPV	ST*	Biomass	Small-Hydro	GST	HD
Emissions ratio	0.45	1.06	0.011	0.017	0.102	0.102	0.38	0.008	0.133	0.004

* The value of Solar Thermal (ST) is assumed to be similar to Solar Photovoltaic (SPV).

2.4. Water pollution (ton/MWh)

Between 2006 and 2008 the European Union conducted the program Cost Assessment for Sustainable Energy Systems (CASES) [30] in order to estimate both internal and external costs of different technologies for electricity generation, considering fuel, and also the stages of construction, operation and decommissioning. Based on published data, values of major pollutants discharged into water for different power generation sources were obtained. Published data were projected to 2010, 2020 and 2030. This study used data from CASES-2030 projection for 2050. The values obtained for conventional and renewable technologies by 2050 are shown in table 5 and 6, respectively.

Table 5 Pollutants discharged into water by conventional sources of energy (ton/MWh).

Technology	GCC	GCC + CCS[a]	Thermal[b]	Coal[c]	Coal + CCS[d]	Nuclear	HD[e]
Pollution ratio	0.02518	0.02744	0.03061	0.16173	0.17402	1.29397	0.0208

a) Natural gas combined cycle with CO_2 capture.

b) Natural gas, gas turbine.

c) Hard coal condensing power plant.

d) Hard coal IGCC with CO_2 capture.

e) Hydropower, dam (reservoir).

Table 6 Pollutants discharged into water by RES (ton/MWh).

RES	Wind[a]	SPV[b]	ST[c]	Biomass[d]	Small-Hydro[e]	GST[f]
Pollution ratio	0.0441	0.3736	0.0197	0.4096	0.0108	0.0197

(a) Wind, on-shore.
(b) Solar PV, roof.
(c) Parabolic through.
(d) Biomass (straw) CHP with an extraction condensing turbine.
(e) Hydropower medium, run of river 1 MW.
(f) For lack of data a value similar to solar thermal is assumed.

2.5. Water consumption (L/MWh)

In the short term, due to the effects of climate change, water use for human activities must be managed and planned more efficiently to avoid future problems of scarcity and quality. Water consumption values by technology were obtained, involving the steps of getting fuel, electricity generation and cooling of process [31], [32], [33] which are shown in table 7.

Table 7 Water consumption by type of technology (L/MWh)

Technology [a]	GCC	Thermal	Coal	Nuclear	Wind	SPV	ST	Biomass	Small-Hydro	GST	HD
(L/MWh)	681	21300	21300	31000	4	114	6470	21300	260	1680	260

[a] Thermal, Nuclear, Coal & Residual Biomass: Cooling by one step.

In Mexico to 2011, 78,400 Giga-liters (GL) of water [34] were consumed. Based on the water consumption by type of technology, the electricity sector´s total value was estimated in the same year, obtaining 2,260 GL, which represents 2.9% of the total water consumption.

2.6. Levelized Cost of Energy (LCOE, US$/MWh)

One of the most sensitive variables with respect to time is the cost of electricity generation. Levelized Cost of Energy (LCOE) is an estimation of the cost of electricity generated by different technologies at the point of connection to an electricity grid, including initial capital, discount rate and cost of operation, maintenance and fuel [35]. This variable is somewhat imperfect because of the externalities that are not included in the market price of fossil fuels, which do not allow a clear and fair comparison with respect to more sustainable ways of generating electricity. However, even with the incomplete nature of market price for fossil fuels, the exercise helps to estimate how technological advancement and widespread use of technologies could define future trends on the energy portfolio to use.

Theoretically each country should calculate their own LCOE (U.S. $ / MWh) as there are endogenous variables that would result in errors when using external data. For lack of local updated data, this exercise was prepared with values released by U.S. Energy Information Administration (EIA) of 2012 [36], which estimate an average LCOE (U.S. $ 2010/MWh) for technologies assuming commercial operation in 2017 (table 8), and considering that in 2050 all the power plants will be new.

Table 8 LCOE by type of technology (US$/MWh)

Technology	GCC	GCC+CSC	Coal	Coal+ CSC	Nuclear	Wind	SPV	ST	Biomass	S-Hydro	GST	HD
LCOE	66.1	90.2	97.7	138.9	111.6	96.5	153.5	243.4	115.4	147.6	98.2	89.2

2.7. Energy Payback Rate (EPR)

If we consider the amount of electricity produced during the life cycle of the technology compared to generating electricity that is required to construct the plant, operate, maintain, supply it with fuel and decommission it, we can estimate a key variable in the studies of Life Cycle Assessment (LCA), the Energy Payback Rate (EPR). Higher EPR´s ratio is indicative of better environmental performance. Table 9 shows the EPR value by type of technology.

Table 9 EPR by electricity generation source ($MWh_{power\ generation}$ / $MWh_{life\ cycle}$). [37], [38]

Technology	GCC	GCC+CCS	Coal	Coal + CCS	Nuclear	Wind	SPV	ST	Biomass	S-Hydro	GST	HD
EPR	4[a]	2.5[b]	3.5[c]	1.6[d]	16[e]	34[f]	6[g]	10.3[h]	27[i]	170[j]	14[k]	205[l]

a) 48% efficiency, average distance, US delivery.

b) This technology reduces the efficiency of power plants by about 25%. Low estimate value of CC´s range was assumed.

c) Coal gasification combined cycle; 43% efficiency; SO_2 scrubbing. Transportation: 2,000 km.

d) Conventional boiler with CO_2 capture and sequestration. Transportation: 2,000 km.

e) Light-water reactors.

f) Onshore, with 35% capacity factor.

g) High estimate value. Low estimate value= 3.

h) High estimate value. Low estimate value= 1.

i) When power is produced from forestry wastes and the distance between the source of biomass and the power plant is short.

j) Run-of-river hydropower, low estimate value. High estimate value= 267.

k) High estimate value. Low estimate value= 2.5.

l) Hydropower with reservoir, low estimate value. High estimate value= 280.

3. Results and discussion.

For the first power demand scenario (349.8 TWh) due to its low electricity energy requirement, the objective of reducing CO_2eq emissions was possible to achieve with relative ease. This allowed a comparison between two portfolios, the first one following the premise of CFE utility to generate electricity at the lowest cost, to minimize LCOE, and a second portfolio more sustainable, to minimize water pollution. Although there is a spread of nearly twice the cost of the portfolio (Min. LCOE vs. Min. H_2O pollution), the spread of pollutants discharged to water is more than 10 times with relative same consumption of water, and a 12.4% improvement in the value of EPR (see table 10).

For the second electricity demand scenario (1147.3 TWh), in the first modeling stage (S-1) three different portfolios were defined based on optimized objective variables (minimum water contamination & consumption, maximum EPR). Since the restriction on CO_2eq emissions was not fulfilled in any of these cases (goal 43.94 million t CO_2eq/yr), an additional generation portfolio was calculated to obtain the energy portfolio that minimizes the value of CO_2eq emissions with not very encouraging results (270.3 Mton). Additionally, secondary constraints were obtained: Minimum Water Contamination value= 80.6 million-tons, Minimum Water Consumption= 3.93E+12 L and Maximum EPR= 9.3.

A second optimization stage (S-2) was run; restricting the model with primary and the new secondary constraints obtained from Stage-1. This new portfolio (Optimal portfolio) did not cover the defined electrical energy requirement, generating only 75.57% of the 1,147.3 TWh initially proposed.

As an additional scenario, it was assumed that Gas Combined Cycle technology could be used to cover the missing energy (Optimal + GCC portfolio). The resulting portfolio even though did not meet two of the primary constraints (CO_2eq emissions and maximum participation of Gas Combined-Cycle technology), whether develop a good balance between secondary and primary constraints (see table 10 for more details). A secondary exercise was proposed in order to obtain comparative data; it was assumed that the Carbon Capture and Sequestration technology (CCS) would have a share of at least 25% with Gas Combined-Cycle and Coal technologies by 2050. Under this new consideration, the optimization model goal was to obtain the minimal CO_2eq emissions (25%-CCS portfolio). CO_2eq emissions of 25%-CCS portfolio were 4.5 times higher than the primary restriction, also showing a water consumption level 3 times higher than the "Optimal + CC" portfolio, besides presenting 3.85 times more water pollution and 21% more expensive, but with a 25.4% improvement in the EPR than "Optimal+CC" portfolio.

Table 10 Results.

Portfolio	Min. LCOE	Min. H_2O pollution	Min. CO_2eq	Optimal + GCC	25% - CCS [a,b]
Generation (TWh)	**349.8**	**349.8**	**1,147.3**	**1,147.3**	**1,147.3**
Cost (million US$)	$36,899.00	$60,154.04	$144,553.21	$123,901.7	$149,888.73
CO_2eq (Mton)	43.94	43.94	270.33	355.83	196.3
H_2O pollution (Mton)	81.72	7.97	333.05	87.66	337.22
H_2Oconsumption(L)	1.23E+12	1.33E+12	1.18E+13	4.12E+12	1.23E+13
EPR	9.5	10.7	9.3	5.9	7.4
Portfolio composition:					
Gas Combined-cycle	17.5%	11.2%	21.6%	54.7%	6.8%
GCC+CCS					12.5%
Thermal					
Coal					
Coal + CCS					2.3%
Nuclear	10.0%		10.0%		10.0%
Wind	25.0%	10.1%	7.6%	7.6%	7.6%
Solar Photovoltaic	22.4%		9.3%	3.9%	9.3%
Solar Thermal		53.7%	16.4%	16.4%	16.4%
Residual Biomass			27.5%	9.7%	27.5%
Small-Hydro	1.0%	1.0%	0.3%	0.3%	0.3%
Geothermal Steam Turbine	13.8%	13.8%	4.2%	4.2%	4.2%
Hydroelectric Dam	10.2%	10.2%	3.1%	3.1%	3.1%

a) CO_2eq emissions ratio for technologies with CCS are assumed similar to Nuclear technology´s value= 0.011 ton/MWh.
b) Water consumption value is assumed similar to the base technology: CC and Coal.

Based on the above results, Mexico should focus on an economic growth plan based on low power consumption to meet its long-term environmental commitments through energy saving actions, high electric productivity and more environmentally friendly technologies. It also shows that low-cost actions in the present are not the most economical for the long run, sustainably speaking.

Moreover, it is essential to have a strong participation of renewable energies to alleviate the global effects of climate change assuring, at the same time, the required energy security as a consequence of a better distributed portfolio. While natural gas is the transition fuel, it is possible to start planning its reduction to less than 20% by 2050, and not continue the trend towards 50%. It is worth mentioning the remarkable participation of CSC and nuclear technology for the reduction of carbon emissions, but still these technologies are far from fulfilling the global requirements of sustainability.

4. Conclusions

Moving towards a sustainable economy requires consuming natural resources efficiently to ensure their access to future generations. In order to identify a sustainable path, estimates were calculated of the portfolio that covers the energy requirement by 2050. For the high energy demand scenario, while the main fuel is still a non-renewable resource -natural gas with a share of 54.7% -, renewable sources could reach up to 42.2% share by 2050, which would help reduce the financial risk and energy dependence.

According to the energy requirement of 1,147.3 TWh projected by CFE, the lowest value of GHG emission reduction, down to 196.3 million t CO_2eq/yr is reached with the involvement of technologies such as CCS, Biomass residual and Nuclear, although this would imply increasing the use of water and its pollution, taking into account that water is the key component for life, with critical expectations of future availability due to climate change effects. In the second high energy demand scenario, an optimal energy portfolio was obtained, that meets both, primary and secondary requirements, but is able to produce only 75.57% of the electrical power demanded. An important question is, whether Mexico really needs so much electricity to grow economically and sustainably. A strategy based on energy efficiency and demand reduction could allow for sustained growth of the country in the following years with less electrical power production. This is in accordance with the first scenario requiring only 349.3 TWh for year 2050, which would allow for low CO_2eq/year production and a diversity of alternative energy sources also providing us with electrical energy security. In other words, this is the best of the scenarios, requiring the continuation of a strong program for using electrical energy with high efficiency.

The increased use of Renewable Energy Sources represents a range of opportunities to boost local industry in order to provide components or complete installation projects. Mexico's renewable energy sector requires a strong commitment by the government to diversify its energy economy, fulfill environmental targets, and decrease energy imports. Mexico must adopt new policies and regulations aimed at encouraging energy efficiency and expanding renewable energy deployment. A more detailed assessment of the LCOE, and its importance in the final decision making process under local conditions, taking into consideration the learning curves to determine the price of future technologies, is needed. These are the issues the authors are currently working on.

References

[1] HSBC Mexico. Doing Business in Mexico. < http://www.hsbc.mx>; 2012.

[2] Organisation for Economic Co-operation and Develompment (OECD). México, Mejores políticas para un desarrollo incluyente. <http://www.oecd.org/mexico/Mexico%202012%20FINALES%20SEP%20eBook.pdf>; 2012.

[3] Consejo Nacional de Evaluación de la Política de Desarrollo Social (CONEVAL). Análisis y medición de la pobreza 2010. <http://www.coneval.gob.mx/medicion/Paginas/Medici%C3%B3n/Pobreza-2010.aspx>; 2013.

[4] Green Growth Knowledge Platform (GGKP). Moving towards a Common Approach on Green Growth Indicators. <http://www.unep.org/greeneconomy/Portals/88/documents/partnerships/GGKP%20Moving%20towards%20a%20Common%20Approach%20on%20Green%20Growth%20Indicators.pdf>; 2013

[5] Ibid 4

[6] Stezaly, A. et al. Externalities of energy production: the hot issue. World Futures 2009; 65: 406–16.

[7] World Energy Councyl (WEC). Comparison of energy systems using life cycle assessment. <http://www.worldenergy.org>; 2004.

[8] International Atomic Energy Agency (IAEA). Energy Indicators for Sustainable Development : Guidelines and Methodologies. <http://www-pub.iaea.org/MTCD/publications/PDF/Pub1222_web.pdf>; 2005.

[9] Krause, R. & Lott, J. Use of the Simplex Method to optimize analytical conditions in clinical chemistry. <http://www.clinchem.org/content/20/7/775.full.pdf>; 1974

[10] Koshel, R. Enhancement of the downhill simplex method of optimization. <http://www.bro.com/resources/kbasePDF/wp_osa_007_enhancement_of.pdf>; 2002.

[11] Cámara de Diputados. Ley para el aprovechamiento de energías renovables y el financiamiento de la transición energética (LAERFTE). < http://www.diputados.gob.mx/LeyesBiblio/pdf/LAERFTE.pdf>; 2008.

[12] Cámara de Diputados. Ley General de Cambio Climático. <http://www.diputados.gob.mx/LeyesBiblio/pdf/LGCC.pdf>; 2012.

[13] Morales-Acevedo, A. (2013), "Forecasting future energy demand: Electrical energy in Mexico as an example case", accepted at ISES Solar World Congress, Cancún, México, 3-7 November 2013. To be published in Energy Procedia.

[14] Secretaría de Energía (SENER). Prospectiva del Sector Eléctrico 2012-2026. <http://www.sener.gob.mx/res/PE_y_DT/pub/2012/PSE_2012_2026.pdf>; 2012.

[15] Ibid 14

[16] Secretaría de Energía (SENER). Estrategia Nacional de Energía 2013-2027. <http://www.sener.gob.mx/res/PE_y_DT/pub/2013/ENE_2013-2027.pdf>; 2013.

[17] The Royal Swedish Academy of Sciences. Energy resources and their utilization in a 40-year perspective up to 2050. <http://www.kva.se/documents/vetenskap_samhallet/energi/utskottet/syntes_energi_eng_2010.pdf>; 2010.

[18] Secretaría de Energía (SENER). Prospectiva del Sector Eléctrico 2012-2026. <http://www.sener.gob.mx/res/PE_y_DT/pub/2012/PSE_2012_2026.pdf>; 2012.

[19] Secretaría de Energía (SENER). Prospectiva de Energías Renovables 2012-2026. <http://www.sener.gob.mx>; 2012.

[20] Secretaría de Energía (SENER). Energía geotérmica. <http://www.energia.gob.mx/webSener/res/0/D121122%20Iniciativa%20Renovable%20SENER_Geotermia.pdf >; 2012.

[21] Comisión Reguladora de Energía (CRE). Evaluación de la Energía Geotérmica en México. <http://www.cre.gob.mx/documento/2026.pdf>; 2011.

[22] Secretaría de Energía (SENER). Prospectiva de Energías Renovables 2012-2026. <http://www.sener.gob.mx>; 2012.

[23] Instituto Nacional de Estadística y Geografía (INEGI). Delimitación de las zonas metropolitanas de México. <http://www.inegi.gob.mx/est/contenidos/espanol/metodologias/otras/zonas_met.pdf>; 2004.

[24] German Aerospace Center (DLR). Global Potential of Concentrating Solar Power. <http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/reaccess/DNI-Atlas-SP-Berlin_20090915-04-Final-Colour.pdf>; 2009.

[25] Red Mexicana de Bioenergía (REMBIO). La bioenergía en México. <http://www.rembio.org.mx/2011/Documentos/Cuadernos/CT4.pdf>; 2011.

[26]Sistema Nacional de Investigación y Transferencia Tecnológica para el desarrollo Rural Sustentable (SNITT). Perspectivas de la Bioenergía en México. <http://www.snitt.org.mx/pdfs/bioenergeticos/Perspectivas_Bioenergia_Mexico.pdf>; 2007.

[27] Instituto Nacional de Ecología (INE). Inventario Nacional de Emisiones de Gases de Efecto Invernadero 1990-2010. <http://www2.inecc.gob.mx/publicaciones/libros/685/inventario.pdf >; 2011.

[28] Santoyo-Castelazo, E. et al. Life cycle assessment of electricity generation in Mexico. Energy 2011; 36:1488-99

[39] Parliamentary Office of Science and Technology (POST) . Carbon footprint of electricity generation. < http://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf>, 2011.

[30] Cost Assessment for Sustainable Energy Systems (CASES). <http://www.ist-world.org>; 2008.

[31] Jones, W. How Much Water Does It Take to Make Electricity? <http://spectrum.ieee.org/energy/environment/how-much-water-does-it-take-to-make-electricity>; 2008.

[32] Nuclear Energy Institute (NEI). Water Use, Electric Power, and Nuclear Energy. <http://www.nei.org/corporatesite/media/filefolder/NEI_Study_Water_June2009_v3.pdf>; 2009.

[33] Webber Energy Blog (WEB). Measuring the Water Footprint of the Energy We Consume. <http://webberenergyblog.wordpress.com/2010/02/21/measuring-the-water-footprint-of-the-energy-we-consume/>; 2010.

[34] Comisión Nacional del Agua (CONAGUA). 2030 Water Agenda. <http://www.conagua.gob.mx/english07/publications/2030_water_agenda.pdf>; 2011.

[35] Lazard Ltd. Levelized Cost of Energy Analysis. www.lazard.com> ; 2011.

[36] Energy Information Administration (EIA). Levelized Cost of New Generation Resources in the Annual Energy Outlook 2012. <http://www.eia.gov>; 2012.

[37] Eurelectric. Life Cycle Assessment of Electricity Generation. < www.eurelectric.org>; 2011.

[38] HydroQuébec. Electricity generation Options; Energy Payback Rate. < www.hydroquebec.com>; 2005.